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MICROSCOPICAL LIGHT IN GEOLOGICAL DARKNESS.

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I.

In appearing before the American Microscopical Society on this occasion, to deliver the usual annual address, I feel that it will be appropriate that I choose my subject and material from the field with which I am most familiar. It is not probable that I can tell anything new or important to those members who have devoted much time and thought to the structure and improvement of the microscope. They are more familiar with these matters than I am, and into this field it would be presumptuous in me to enter. Nor is it likely that I can give many of you any instruction in microscopical technique. With me the microscope is and has always been, ever since I began to use it for research, an implement much employed at times for the prosecution of my work in teaching and in investigation, and then laid aside until another occasion called it forth. I can make no profession to being a technical microscopist.

I could not hope to rival or surpass the address of my predecessor in this chair on the limits of the visible or many of the interesting and laborious investigations which have formed the topics of yet earlier presidential discourses. The purpose of the Society is, in my opinion, better served by bringing forward something specially belonging to the field of investigation, in which the speaker is at the time and has, perhaps for many years, been engaged. By so doing the danger of repetition and of overlapping is avoided, for the fields of labor are so numerous and so different that it can scarcely happen that two successive presidents will be employed in the same department. Another advantage is also secured by the adoption of this plan. His fellow-members are, so to speak, personally conducted by the speaker over fields which they would otherwise seldom or never visit, and are made acquainted with work and results of which they must, but for some such opportunity, remain ignorant through lack of time to do the necessary reading and study.

The field of nature, which has more particularly engaged my attention—the field of geology—is of immense extent and borders on those of zoology and botany, into both of which the geologist is compelled to make long and frequent excursions in order to gain the knowledge and experience that will alone keep him from useless labor and erroneous results in his own department.

I will, therefore, ask you this evening to accompany me on a short trip through a part of my own favorite field of nature, where I will be your guide and Cicerone, and where I trust that you will all find something worth the time and the patience which your presence here this evening shows that you are willing to devote.

The portion of the geological field which I have chosen for our excursion is that in which the microscope is the most important instrument of investigation. It is, therefore, one in which the geologist and the specialist in microscopy can both feel an interest. It is also one in which this engine of

investigation has but recently been employed to any great extent, and may, I hope, to some of my hearers possess a little of the charm of novelty.

I have entitled the address Microscopical Light in Geological Darkness, but its scope would be equally well expressed had I called it The Microscope in Geology.

II.

To the geologist the year 1858 is a memorable epoch in the history of his science. At that date the now veteran worker, Mr. H. C. Sorby, of Sheffield, England, published his first paper on the Microscopic Structure of Rocks[1], in which he showed the vast possibility that the new power had brought within reach, or to maintain our figure, the great extent of the dark unknown which the new light would illuminate. Passing by for the moment the immediate subject of that memorable essay, to which I will return anon, I must explain that Mr. Sorby was the first to investigate the microscopic structure of rocks by means of thin sections.[2]

The aid which the lapidary could give had not previously been asked in this work. It had not been considered likely that any mysteries would be revealed by a study of what

1. Dr. H. C. Sorby inaugurated his year of office as president of the Sheffield Literary and Philosophical Society by giving an address upon a half century spent in scientific work. During this time he has published more than one hundred papers. The earliest was in 1847. In 1849 he prepared the first transparent microscopical sections of rocks, on which he issued a paper in 1850, wherein most of the modern methods were adopted. From this subject he was led on to that of meteorites and meteoric iron. Then he undertook an investigation of the microscopical structure of iron and steel by new methods and with new illuminators. This led him to the invention of the direct-vision spectrum-microscope and other apparatus. From this he passed on to study the coloring matters of animals and plants. Thirty years ago he received the Wollaston medal from the Geological Society. The Dutch Academy of Science awarded to him its first Boerhaave gold medal, and the Royal Society conferred on him a gold medal in 1874. Oxford gave him an honorary degree of LL. D.—*Nature*, February 11, 1897

2. It is scarcely necessary for me to explain to any members of the Society the methods of petrography. Thin chips or sawn slices of the minerals are smoothed and polished on one side, cemented to a glass slide and then smoothed and polished on the other. Few minerals are so opaque as to refuse to become transparent or translucent. The introduction of the new abrasive substance, carborundum, has proved of great value to the petrographer, enabling him to reduce the cost by using this powder instead of diamond dust.

were classed as the metamorphic rocks. But the collateral advance in various departments of physics had provided new machinery and established new positions, and Mr. Sorby boldly advanced to the examination of these polymorphic masses, which had long figured as granites, gneisses, syenites, greenstones, etc., and regarding which diverse and contradictory views had been held. The art of cutting and grinding thin transparent slices of these minerals, introduced by Mr. Sorby, has now been developed so as to have become one of the most important aids to microscopical geology, and the dark and tangled problem of the crystalline rocks and crystalline schists, when some day solved, will be solved largely by the invaluable assistance which this device has bestowed upon the investigator.

As an example of what I mean, let me adduce the case of certain quartzites, supposed by some to be of non-sedimentary origin and therefore to differ radically from other quartzites and sandstones. I should explain that to the geologist a sandstone is nothing but an ancient seabeach or lakeshore and the sand is the material of more ancient cliffs and bluffs which have been broken up by the waves and ground down by long-continued dashing on the shore. Every grain of these sandstones shows its origin by its form. It is worn and rubbed till all the points and edges have been rounded off and it is in fact a microscopic pebble. Sandstones are the monuments of extinct geography and, though now far inland, show us where, in times gone by, the land and water met. The geologist can almost hear the roar of the waves as he gazes through his microscope on the tiny quartz grain that has suffered such tribulation, but which has endured in consequence of its hardness—a case, we may presume, of the survival of the fittest. He is reminded of Tennyson's lines:

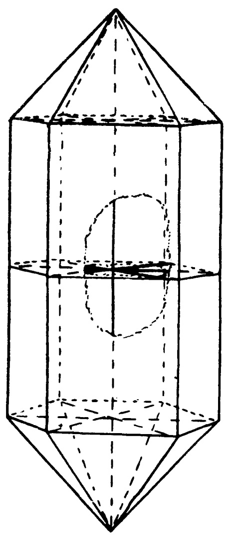
> Here rolls the deep where grew the tree
> O earth, what changes thou hast seen
> Here where the long street roars hath been
> The stillness of the central sea.

But the sandstones to which I allude showed characters which did not agree with those usually seen. The grains did not appear to be rounded. They seemed to possess the sharp and angular form of quartz-crystals, hence they were claimed as products of igneous, or at least of metamorphic action. But after grinding down thin slices and subjecting them to microscopic examination it was soon proved that every grain of the rock had once been as well rounded as were those of the most typical sandstone, and that the deceptive appearance was due to a secondary growth of quartz since t deposition of the sand. So obvious was this that the worn outline of the primitive grain could be readily traced by a thin film of limonite encrusting it, outside of which the new growth had taken place. This was clearly demonstrated in the case of a quartzite from Wisconsin by the late Prof. R. D. Irving, who published a striking illustration several years ago, where the solidification of the rock, converting it from a sandstone into a quartzite, had been induced by a secondary growth of younger quartz, which, acting as a bond, had filled up the interstices and cemented the whole into one hard, solid mass of silica.

In consequence of these discoveries all such sandstones and quartzites were removed from the Archean or igneous domain and established permanently as parts of the great system of stratified rocks, many of them being among the most ancient of the class.

Yet a further step followed. The microscopist has at his command another instrument, sometimes more effective than his special favorite, and when combined with this, adding immensely to its power. The polariscope aids the microscope and the polarised beam often reveals what would otherwise remain unseen. The structure of most crystals is such that they possess different moduli of optical elasticity. That is to say, they transmit light with different velocity in different directions. This is very strongly marked in some substances, of which quartz is one. The consequence is that

when a polarised beam passes through a thin plate of one of these minerals and afterward through the analysing nicol interference is produced, part of the pencil is extinguished and the remainder of the rays exhibit the magnificent spectral tints which are nature's language in revealing her secrets. The slide which, under the microscopic objective alone, shows merely the outlines of the structure glows under this light with a splendor of color only to be rivaled by the spectrum itself. Every crystal, with few exceptions, comes out in the tint due to its position in the rock and changes this tint with kaleidoscopic quickness and beauty as the analyser revolves. Translating this color-language of nature and applying it to the sandstones in question we find that it tells us the direction of the crystallographic axis, and therefore enables us to recognise the position of every quartz grain. By so doing we learn that the rounded and worn fragment has grown just as broken crystals grow and renew themselves in our laboratories, and that the secondary quartz taken on during the rejuvenescence of the crystal has been taken on accurately on the original lines. In other words, the part of the quartz-crystal outside the zone of limonite is oriented optically and crystallographically in exact agreement with the original worn sandstone grain within that zone. The same law of growth that dominated the young crystal survived its severe attrition and partial destruction and at length, after ages of rough usage and wear and tear on a sea-beach, resumed its sway when conditions again became favorable, and showed its sustained supremacy by dominating the subsequent accretion of quartz when crystalline growth again began.



SAND-GRAIN WITH SECONDARY QUARTZ.

Fig. 1.—Showing the worn grain of sand and its crystallographic axes around which secondary quartz has accreted so as to reconstruct the crystal on the original lines.

But in another direction also the geologist has profited by the light shed abroad over his field by the microscopist. The study of these thin slices by the aid of polarised light has revealed other facts of immense significance to the petrologist and as unexpected as they are significant.

It is among the ancient rocks of our earth that the microscope has won and is winning its greatest triumphs. In that wilderness of Archean crystallines, where few dared hope ever to find any limits or boundaries—that sea without a shore—that worse than Serbonian bog in which to plunge seemed certain oblivion, "wherein length, depth and height and time and space were lost"—here the microscope is revealing limits—is providing a compass—is pointing out solid stepping places where safe footing may be found and steady progress made. Those who are not practical geologists cannot realise the immense difficulty of studying the massive so-called primary rocks. The gneisses and granites and crystalline schists that underlie the stratified sandstones, shales and limestones have hitherto been an insoluble enigma. Were they of igneous or aqueous origin? Were they part of the original crust as it consolidated from fusion or were they later deposits, subsequently altered and crystallised? Was gneiss essentially and always an Archean rock, or was gneiss a product of any age under certain conditions? These questions divided the geological world and agreement seemed impossible. The long conflict between the Plutonists and the Neptunians was not more severe or more hopeless.

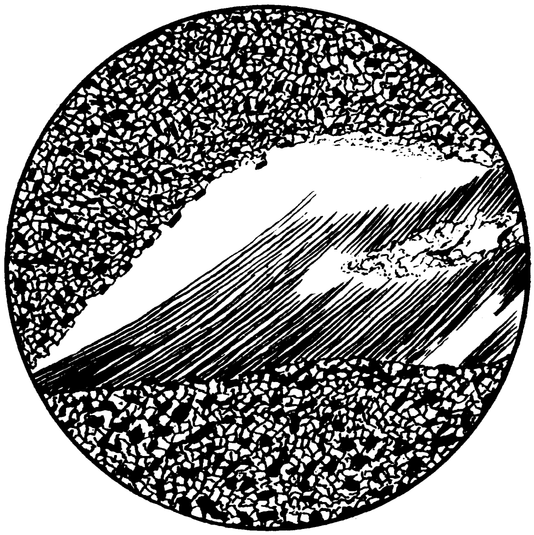
The importance of the problem is evident when we consider the immensity of these rocks. Look, for example, at the huge mass of gneiss which composes the surface rock over a large part of Canada. Stretching in a vast curve from the Atlantic coast of Labrador through Quebec and Ontario north of the Great Lakes and thence away toward the Arctic ocean and forming the basement of the whole geological column, it has been well named by the Canadian geologists the Fundamental Gneiss. Of immense, but unknown, thickness it

presents a monotonous complex of crystalline minerals, among which quartz, orthoclase, mica and hornblende are by far the most abundant and characteristic.

But whether these are metamorphic sediments or the product of a liquid original magma was an unsolvėd problem. And no method of reaching a solution was found until the new science of petrology supplied it. Within the past few years great progress has been made in the investigation. Thin slices of this and other similar gneisses have been cut by the thousand in the different laboratories of the world. Laid on the stage of the microscope between the crossed nicols they have supplied strong and unexpected evidence. On one may be seen a crystal of quartz in good condition, giving extinction of the polarised ray at once and complete in all parts at the same instant and angle. In another is found a similar fragment in the form of a thin plate, whose irregular extinction, though slight, shows plainly that some great change has come over it since it was enclosed in its matrix. The original crystal has been in some cases flattened down so as to form a thin lamina in which all the regular structure and the previous molecular arrangement of the crystal have been abolished. The previous axes of optical elasticity no longer betray their symmetrical positions by uniform interference-colors. They are broken up and displaced as though some violent disturbance had happened to them. In like manner a crystal of plagioclase felspar may be found in which parallel planes of granular felsite, intersecting the mass, are revealed by this delicate test. Similar phenomena appear in the case of hornblende. The crystal does not show the original sharp outline and definite form, but is flattened, distorted, often fractured, and not unfrequently a line of particles is seen tailing off from it in one direction like the wash from a rock exposed to the action of a stream of water. Mica, too, exhibits like appearances, and the particles of an original crystal will often form a distinct black layer to a short distance to the leeward, so to speak,

of the remaining portion. In this way the so-called "augen-gneisses" of the petrologist have been formed. Thus the action of all these minerals, and the same is true of others, indicates the action of some secondary force which has caused momentous and destructive changes in the original crystals.

Data, such as these, undiscoverable by the naked eye, come out in brilliant colors and sharp outlines on the stage of



PLAGIOCLASE CRYSTAL—PARTLY CRUSHED.

Fig. 2.—Showing the remains of a crystal of plagioclase felspar in the middle, with crushed felsite above and below and partly formed layer of the same through the middle. The white portion represents a region where crushing had commenced, but ceased on relief of pressure.—From Dr. Adams's Report, Geol. Surv. of Canada. 1896.

the polariscopic microscope, and it is only necessary to learn to read the hieroglyphics of nature in order to translate them into the language of man. When this is done we find that they all have one bearing and point in one direction. They speak all with one voice and their words are clear and emphatic. The injuries which the crystals have suffered, their consequent irregular action on polarised light, tell us plainly that they have been subjected to the action of some resistless force since their formation, and that this force has

produced earth-movements whose effects are shown in the crushed and mangled condition of the component mineral crystals.

These destructive changes could not have taken place when the rock was in a liquid state. Only after consolidation of the magma and the crystallisation of its component minerals could their fracture and crushing become possible. Evidently, then, these gneisses are the product of great heat and this, with their immense extent, prevents our regarding them in any other light than formations of very ancient date —genuine Archean rocks.

It may be difficult to believe that a fragment of so hard and brittle a mineral as quartz could, by any force whatever, be flattened out into a thin plate, but the evidence allows no doubt on this point. Under these terrific pressures the crystalline structure of the gneisses has broken down and a granular condition has resulted. Crystals of quartz have been crushed into quartzite and crystals of felspar into felsite. Hornblende, being tougher, has been squeezed and flattened down into thin plates and a laminated structure developed thereby in the rock-mass, while mica, often the product of these pressures, has in like manner contributed to render the previously compact mass schistose and flaky.

Beside these manifest indications of excessive force exerted on the crystals there are others less distinct, traces of incipient yielding—molecular displacements—"strain-shadows," so to speak, which betray the intensity of the compression to which this fundamental gneiss of Canada has been subjected. The crystals have been caught, as it were, in all stages of their crushing, and the record of the process is complete.

It is not our business this evening to ask the causes of so mighty a force exerted within the earth or to answer our own question. To the physicist the problem presents no great difficulty. But looking at these thin sections and realising their unanswerable testimony, the geologist almost

feels the fearful strains which have torn asunder, as it were, the very fibers of the solid crust. As he looks at the wounds and rents in these crystals he sees them laboring to adjust themselves to the pressure and hears the sounds of the cracking and crushing which follow their failure to comply instantly with the peremptory demand. The slightest variation in pressures so enormous must be followed by movement and this variation of pressure must have been incessant. Hence the crushed condition of the crystals and the evidence of continual "creeps" in the gneiss in order to adjust itself and maintain its equilibrium of the mass. Hence, also the geologist realises the continuity of the internal mass and the absence of joints and fissures. He is convinced that at the depth of a very few miles no cavity in the crust can possibly exist, for under a gravitational force so intense, the whole mass, of whatever consisting, must be plastic as wax, every incipient cavity being filled, so to speak, before it was opened.

Yet more than this has been revealed to us. Not only have the separate crystals of the rock thus given way under the enormous earth-strains, but the mass, as a whole, during and after crushing, has flowed like a liquid in the line of least resistance. Hard granite and tough diorite have alike yielded and have been squeezed like putty so that flow-lines have been developed and a schistose or slaty structure produced.

Tresca's well-known experiments many years ago convinced us of the possible flow of refractory substances under adequate pressure. Even cold iron was squeezed out as wax. But the materials with which Tresca worked were not brittle like crystals of quartz, felspar, etc. Tresca also had not in his power the pressures that the geologist can demand or the long æons that geology can summon. Grant these and the microscope and the polariscope combined give us evidence that cannot be gain-said, that even these brittle minerals of the great fundamental gneiss of the Canadian highlands have been squeezed out until their constituent particles, in the

effort to escape the tremendous pressure, have slid over one another as those of a viscous mass. Yet though compelled to move because the equilibrium was disturbed, they were unable to move out of their spheres of mutual cohesion so that, though sheared, their continuity has not been destroyed. The gneiss or the granite has crumbled, but the crumbs cohere and it is one mass still though its form is changed.

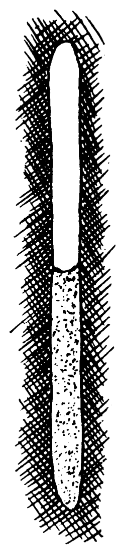
One step farther the geologist can safely advance by inference. Strains so enormous could not be developed at or near the surface of the globe. Relief would soon be found there by upward movement. The pressure indicated by our polariscope must have been deep enough to be produced in great part by the weight of the overlying strata. What depth would be required for this purpose it is not possible yet to determine with exactness. But as we have in Pennsylvania and elsewhere strata now at the surface which were once certainly several miles below it, and as these strata show not the least sign of having undergone any such treatment as that which I have described, it is safe to conclude that the rock now forming the surface of the Laurentide Mountains must once have lain at a still greater depth. Such possibilities are not easily realised unless the mind dwells on the thought. That the now bare gneissic rocks of Canada were once covered with a thickness of many miles of the same material, is a daring deduction from the study of a microscopic slide only one hundredth of an inch thick and less than a square inch in area. But denial is more daring still. As Playfair wrote in his celebrated essay on the Huttonian theory: "Reason can sometimes go where imagination dares not follow."[1]

1. Not to carry this argument farther in the text I will add here that, inasmuch as it is quite certain that no such mass ever existed at any one time on the Laurentide area, it is necessary to adopt the view that a slow elevation of the region has been in progress through geologic time and that elevation and subsidence have approximately equalled and counteracted each other ever since the movement began. Resting on this, some geologists have gone farther and have taught that the mountain masses of the earth are such in consequence of the inherent levity of their materials, and that, on the other hand, the ocean abysses are sunk because their floors consist of matter inherently denser and therefore floating lower in the viscid core.

III.

But even this is far from acknowledging to the full the debt of geology to the microscope. Indeed, it seems as if the future were more charged with promise than the past with performance. In another part of the field the same veteran observer and worker has led the way and new prizes have fallen to the lot of him and his followers.

Gems and other crystals had long been known, especially since the time of Brewster, to contain minute cavities partly or entirely filled with a liquid whose nature was unknown. But by the study of a few specimens Sorby succeeded in determining it in several cases. Among these was one which deserves to become classic on account of the peculiar advantage which it gave to our pioneer in the investigation. This *was*, indeed I hope I may say it *is*, though I do not know its present abode, a sapphire containing a cavity of a tubular form. It was so regular in its bore that it served the purpose of a natural thermometer, and by its use Mr. Sorby reached a conclusion at once surprising and important. I should mention that this little thermometer was one-fourth of an inch long by about one-eightieth of an inch in diameter, a truly microscopical instrument. It is represented, greatly magnified, on the diagram Fig. 3. On experimenting with this little instrument Mr. Sorby found that the liquid, which, as shown, filled one-half of the cavity at ordinary temperatures such as 50° F., expanded so rapidly that its volume was doubled and the cavity was full at 89° F. This increase of bulk within so narrow limits of temperature



SAPPHIRE WITH TUBULAR CAVITY.

Fig 3.—Mr. Sorby's microscopical thermometer, magnified about twelve times, showing the liquid carbon-dioxide.

at once excluded all ordinary liquids, and by further investigation and comparison Mr. Sorby was able to decide that the substance was nothing less than liquid carbonic acid, the only known liquid whose rate of expansion was equally great. Here was a solid fact contributed by the microscope toward the solution of some of the difficult and complicated problems presented by the physics of the earth's crust, and, again, we shall find that from this study of a drop of liquid almost infinitely little, contained in an instrument equally minute, may flow results of great moment and far-reaching consequence. It is not the size but the solidity of the premises that authorises the conclusions. Granting, as we must, that the little drop is carbon-dioxide in the liquid form, we can safely advance by reasoning on the known properties of this substance somewhat as follows:

The critical temperature of carbon-dioxide is about 88° F. (87.6°), that is to say, above this it exists only as a gas, and can by no pressure be liquefied. Now it is in the highest degree improbable that at the time and in the conditions when the crystalline rocks were formed the surface of the earth was below this point. On the other hand, we may confidently rely on its having been far above this critical temperature. Obviously then the carbon-dioxide must have been sealed up in the crystals in a gaseous state—a bubble of carbonic anhydride. Here the problem becomes indeterminate. Both the original temperature and pressure are unknown. But arguing from what we know of the physics of this substance we may deduce the following conclusion: At present ordinary temperature, 50° F., the pressure in the microscopical registering thermometer of Mr. Sorby, must amount to about forty-eight atmospheres or 720 pounds on the square inch. This little instrument was exactly filled at 89° F., very near the critical temperature. At this point the minimum pressure which will enable the carbonic anhydride to retain the liquid state is seventy-three atmospheres or 1,100 pounds on the square inch. Consequently, if as inevitable, we assume a higher

temperature than 88° F. for the globe at the time of the crystallisation of the minerals, we must also assume a higher pressure than seventy-three atmospheres as one of the conditions prevailing during crystallisation.

This, however, is doubtless far too low for both. Instead of 88° Mr. Sorby and others consider the temperature of consolidation to have been nearer 700° F. Mr. J. C. Ward, a few years ago, following in the footprints of Mr. Sorby, carried his work a little farther. Assuming his datum of 680° F. as the temperature of crystallisation of the minerals, he shows that the corresponding pressure was not less than twenty-six tons, or 3,500 atmospheres on the square inch, and that these microscopic flasks must have been charged with their effervescing contents under that enormous compression.

This is equal to the weight of a mass of overlying strata 52,000 feet thick. It is not right, however, to attribute the whole of this to the weight of overlying strata. There is no doubt that it is a resultant of this and the violent lateral compression to which the contortion and folding of the gneiss is due. The latter is probably the larger of the two components. Mr. Ward's conclusion is that the granite of Skiddaw, in England, was formed at least six miles below the surface, a depth at which the temperature is normally very near Mr. Sorby's datum of 680° F.

This is surely a vast deduction from data, microscopically minute, and seemingly insignificant. But insignificant as one of these "crystal flasks," as they have been aptly called, may be, we are not dealing with one alone but with vast numbers, for investigation has revealed them by myriads and by millions, and not in gems only, but in other crystalline minerals. In size they range between the one-thousandth and the fifty-thousandth of an inch, but they are so multitudinous as often to impart a white tint to the crystal, and many specimens of milky quartz owe their whiteness solely to the presence of these innumerable bubbles. In some of the Cornish granites the cavities make five per cent. of the vol-

ume, and yield four pounds of the liquid to every ton of the rock.

Mr. Ward says: "Such is the minuteness of these cavities and their number in many cases, that more than a thousand millions might be contained easily within a cubic inch of quartz." We shall presently quote another writer giving the same testimony.

IV.

I must here digress for a short time from the main line to trace a tributary that meets it at this point and whose course it is necessary to have in mind in order to develop the argument. The geologist, regarding the past history of the globe with a critical eye, has long been amazed at the vast masses of mineral fuel—coal, petroleum and gas—which he finds accumulated in the crust and especially on one horizon. The carboniferous system, with its huge stores of free carbon, the chief and almost the only resource of the world at present for heat and power, and its hope for the future are to him a standing enigma. The botanist assures him that all has been extracted from the atmosphere by the agency of green plants, under the stimulus of sunshine. No other process is known whereby this precious element can be severed from its compounds and isolated in free form in any appreciable quantity. Indeed its separation in the laboratory is a somewhat difficult and refined experiment. But this assurance of the botanist darkens rather than clears the enigma of the geologist. Relying with confidence on the botanical principles of his brother-student, which are confirmed by so many concomitant proofs as to be quite unassailable, such as the vegetable structures, leaves, stems and fruits found in the coal, he is yet unable to see where these plants obtained so vast a supply of carbon. From a careful quantitative study of the atmosphere he learns that the sum total of this element therein contained is vastly less than that which now lies

buried in the earth, so that to accumulate another stock of mineral fuel equal to that which we are now using so freely and squandering so recklessly, would be an impossibility. The material is not present in the atmosphere, and what is not there can not be taken away. Without troubling you here and now with the calculations, I will merely give sufficient results to establish my statement and to enable you to follow me with confidence. The whole amount of carbon in the air to-day, in the form of carbon-dioxide, does not exceed 150 to 200 cubic miles—a sufficiently large amount you are ready to say when you try to realise what it expresses. A single cubic mile of coal almost passes comprehension. The world's entire annual consumption does not exceed 350,000,000 tons, so that one single cubic mile, or 7,000,000,000 tons, would suffice to supply us all for twenty years. But the stock of coal and the like, actually in the ground, far exceeds, as I have said, even this enormous figure. To attain anything like exactness in such data is manifestly impossible, but we cannot assign to the world's store of mineral fuel, or the coal contents of our coal fields, oil fields and the like, a less amount than 2,000 cubic miles at the least, or about ten times what could be obtained from the air. Here lies the enigma, and, as you see, the botanist has not furnished any interpretation of it.

It is easy to say, as many have said, that there was a larger supply of carbonic acid in the atmosphere then, than there is now. This is cutting rather than untying the Gordian knot. Perhaps it was so. The explanation is plausible. But the plausible in nature is not always or usually the true.

Time will not allow a full discussion of this topic this evening. It must suffice to indicate, in a general way, the reasons which preclude us from accepting the reply as good and sufficient.

In the first place, let us consider the demand of the geologist. We have mentioned the coal beds, the oil and the gas,

but these are far from being all that he requires. There are in the earth huge beds of black shale, holding often from 5 to 15 per cent. of carbonaceous matter. This far exceeds the mass of the coal and we may safely put the figure up from 2,000 to 20,000 cubic miles. Alexander Winchell's total is nearer 30,000. Then the vast stores of peat and the whole animal and vegetable creation, or at least the carbon which they contain, must be included, and this defies exact calculation. Lastly, the mass of coal that has been destroyed by erosion must be added—small though it be beside the vast total. Considering all these it seems perfectly safe to set down the mass of unoxydised carbon in the earth's crust at 50,000 cubic miles, or 250 times as much as that now existing in the air—a proportion of 10 per cent.

Facing this fact the botanist is scarcely willing to admit that plants could flourish in such a medium. Ferns and their allies have been grown in cases charged with an atmosphere containing 10 per cent. of carbonic anhydride, and possibly so large a proportion may have been consistent with the existence of the cryptogams of the early eras. Botany cannot give an absolute denial. Experiments on this point are few and not very definite. Prof. Daubeny, of Oxford, stated nearly fifty years ago, in a paper read before the British Association in 1849, that ferns and their allies cannot bear more than 10 per cent., but could exist in an atmosphere containing 5 per cent. of carbon-dioxide. Prof. Boussingault reported, in 1864, that different plants flourish best in atmospheres ranging from 8 per cent. downward. We may therefore infer that the above requirement of the geologist is close to, if not above, the limit of tolerance of plants allied to those by which the mass of our coal was made, and that on this ground it is scarcely tenable.

On the zoological side the evidence is also uncertain. Some of the lower animals, such as fishes and amphibians, are tolerant of a far larger amount of carbon-dioxide than can be endured by the higher groups. But it can scarcely

be probable that even they could live in an atmosphere containing as much as 10 per cent.

However, setting aside both these as inconclusive, a physical objection remains to be considered of more serious import. By calculation we find that the conversion of this mass of carbon into carbon-dioxide would absorb all or nearly all the oxygen in the air and leave it devoid of that essential element. We may, therefore, safely assert that whatever the earth's atmosphere may have been in *very early* times, the carbon now in the crust cannot have existed as carbonic acid in the atmosphere at any one time since animal life began.

Returning, then, to our former ground we see that, without dogmatising on the primitive atmosphere, we are unable to accept this plausible explanation as a good and sufficient solution. We cannot hypothecate a sufficient capital stock of carbon to meet the immense and continuous drafts that have been made upon it.

So strongly did one of our most able chemical geologists, the late Dr. Sterry Hunt, feel this difficulty, that he was driven to make the suggestion that the earth had picked up the needed material from the space-realms during her annual and secular journeys—a remark which Alexander Winchell says is "highly suggestive." But if we can realise the figures of some modern molecular physicists regarding space we can hardly entertain the suggestion, for they tell us that in the interplanetary regions there is only one molecule of any kind in 10^{314} cubic miles of space. In such an absolute, awful solitude, the earth can surely not have been able to gather up the needed carbon-dioxide, though she had sought it from pre-Cambrian times down to the present day.

V.

But here the microscopist comes upon the field and offers his services in the cause of peace. In diplomatic language, he proposes to act as mediator. He points out, as I have

already said, the minute cavities existing in the crystalline rocks and shows that in them is hidden a store of carbonic acid, hoarded, as it were, in the pockets of mother earth, infinitesimally small but infinitely numerous, and he suggests that possibly here a source may be found from which the geologist may get his coal and the botanist his carbonic acid, without alarming the zoologist for the safety of his animals. He shows that on this view it is no longer necessary to assume its presence in the atmosphere all at the same time. Instead of this he suggests that it may have been, and probably was, set free almost atom by atom as the crystalline rocks yielded to erosion and these "sealed flasks" were, one after another, burst open by the pressure within.

At first blush we may be disposed to laugh at the suggestion and to deem such microscopical contributions of small comparative value when so vast a demand is made. But it is well to recollect that "many a little makes a mickle." Let us look at the matter quantitatively for a moment, for here must lie the crucial test. If our theory fail here it fails altogether, though if it pass this test its ultimate success is not hereby assured.

Since the investigation by Mr. Sorby, to which I referred at the outset, little advance has been made until quite recently, when a stimulus was given to new experiments by the marvelous discovery of argon in the atmosphere. The distinguished chemists who were engaged in that most remarkable investigation turned their attention to the gases contained in various minerals, among which were those of the crystalline rocks. And in a paper recently read before the Royal Society (March, 1897), Professor W. A. Tilden stated, as the outcome of some work on quartz, felspar, and the other constituents of granite, gneiss, gabbro, schist, basalt and other minerals, twenty altogether, from different horizons and widely distant localities, that they all yielded gas in which hydrogen is the preponderating element. Next to hydrogen the most abundant is carbonic acid. And

he further makes the important statement that the volume of gas given off by these rocks, and which comes entirely from the minute cavities within them,[1] ranges from 1.3 to 17.8 times the bulk of the rock; that is to say, that a cubic mile of stone would give out from one to seventeen cubic miles of gas. Considering these figures the problem begins to assume a new aspect and our next question is, How many of these cubic miles of rock have we at command? Because it is evident that if we only have miles enough we can get enough carbon-dioxide.

At this point in the enquiry I was stopped for a while. How is it possible to ascertain the amount that has been worn off the surface of the crystalline rocks since geologic time began? I laid the subject aside for a time. But soon the thought occurred that the mass of the sedimentary rocks, with a few corrections, must equal the amount worn off the crystallines since the days when these latter composed the whole surface. But it is not easy to obtain even this datum and any result must be merely approximate.

I may here be allowed to digress for a moment to explain. All geologists who accept the principle of cosmic evolution (and in the present day few can be found who reject it) are agreed that the earth has cooled and consolidated from an early liquid mass, consisting of slaggy, glassy and stony material, resembling modern lavas. From this hard and intractable rock-mass all our sandstones, shales, clays and limestones have been slowly separated by the disintegrating and dissolving action of water. Over and over again have these strata been broken up and swept away by rains and rivers, until the ancient crystallines have gradually been buried under their own ruins and now occupy comparatively a small part of the surface. None the less has every particle

1. As a proof of this fact Professor Tilden incidentally remarks: "The gas is apparently wholly enclosed in cavities which are visible in thin sections of the rock when viewed under the microscope, but as they are extremely minute, very little gas is lost when the rock is reduced to a coarse powder, and as a result of experiment in one or two cases I find that practically the same amount of gas is evolved on heating the rock, whether it is used in small lumps or in powder."

of the sedimentary strata, except carbon and carbon-dioxide, been derived from their steady destruction, the amount of which must, of course, be approximately equal to the mass built up from their ruins.

Had the geologist senses sufficiently exalted he might hear the miniature explosions, as one after another, or, many at the same instant, these little "sealed flasks" burst and discharge their highly compressed contents. In grinding down a thin slice, myriads of them are opened and their gases lost. So in nature, as erosion thins down their crystal walls, these ultimately become so weak that they can no longer withstand the bursting pressure within and a microscopical explosion ensues.

The area of the dry land of the globe equals about 60,000,000 square miles, and by far the greater part of it is covered with thick sheets of sediment. Deduction must be made for the areas where these are absent and the old crystalline rocks still form the surface. But, on the other hand, a large addition is due on account of the sea-margins which for 200 or 300 miles from shore are covered with the wash from the land. With the deep sea I will not here deal.

I assume, then, that one of these corrections will countervail the other and that the area of the sedimentary strata is equal to that of the present dry land or 60,000,000 square miles. Now the thickness of these rocks is very various, ranging from ten miles down to nothing. The former figure is seldom found, but it appears to me that to assume an average depth of one mile is not unreasonable. This will give us for the whole mass eroded from the ancient crystalline rocks the sum of 60,000,000 of cubic miles.

Regarding the quantity of carbon-dioxide contained by the rocks on which Professor Tilden experimented, the following figures are taken from the report of his paper given in the *Chemical News* for April 9, 1897:

			In 100 vols.	
		Vols.	CO_2.	H_2.
Tilden.	Granite, near Dublin, acid, Plutonic	5.0	9 4	90 6
	Granite, Ardshiel, acid, Plutonic	6.9	79 5	20.5
	Greisen, Altenburg, Sax., altered, Plutonic . . .	1.8	13 6	86.4
	Granulite, India, altered, Plutonic	2.6	48.7	57.3
	Quartz-Schist, Co. Down, Metamorphic	2.8	23.0	77.0
	Fuchsite Schist, Baroda, Ind., Metamorphic . .	4.2	20.8	79 2
	Corundum Rock, Rewah, Ind., Metamorphic . .	3 5	26.0	74.0
	Pyroxene Gneiss, Ceylon, Metamorphic	7.3	84.4	15.6
	Gneiss with Corundum, Seringapatam, Metamorphic	17.8	18 0	82.0
	Gneiss with Garnet and Graphite, Ceylon	4.5	11.0	89.0
	Gneiss, Himalayas	7.2	11 5	88.5
Dewar and Ansdell.	Gneiss	5.3	82.3	13.6
	Felspar	1.3	94.7	2 2
		13—70.2	13—522.9	
		5.4	40.	

These results give us an average of five and a half volumes of gas from every volume of rock, and of this quantity 40 per cent. was carbon-dioxide. Combining the averages we find that these Archean minerals yielded between two and three times their volume of carbon-dioxide. Combining again with the previous result—60,000,000 cubic miles of eroded crystalline rock—we obtain about 150,000,000 cubic miles of gas. Of this the three-thousandth part will be carbon in the solid form.

In this way the final result is reached; that by these minute contributions we get about 50,000 cubic miles of carbon, equal to at least 60,000 cubic miles of coal. As the total stock of existing coal amounts to only about 2,000 cubic miles, or with all the other forms of unoxydised carbon, to not more than 50,000 cubic miles, we have a supply ample and more than ample for the demand.

In such an investigation I need not caution anyone against laying much stress on the exact figures here given. A calculation when the data are so indefinite can but be approximate. Yet I hope I have shown that allowing for all inaccuracy we

have here a supply of the precious element, carbon, from which the geologist can obtain his coal without offending his brethren, the botanist and the geologist, by insisting upon a greater amount at any time in the atmosphere than they are willing to allow. Here we have a supply from which it can be drawn as wanted without disturbing the existing balance of atmospheric composition, or compelling us to assume that in the early days of life the air was materially different from what it is at the present time.

I am sure it must be interesting to the working members of the American Microscopical Society to see how the investigation of these minute bubbles in the crystalline rocks leads on to the discovery of a possible origin of the carbon in our coal. To any geologists present I must excuse myself for considering only one part of the problem and saying nothing of the other stores of this carbonic acid in the rocks of the earth compared with which the coal and other free carbon in the earth is a mere vanishing quantity. But the conditions differ and the solution of that problem must differ also.

The unconsidered elements would, if introduced, vastly and unduly extend this discussion, while they would not in any way conflict with what I have said. They would complicate, but not invalidate the argument. I have merely endeavored to put forward and maintain a mechanism whereby carbon-dioxide could be obtained as wanted by the plant-world without charging the atmosphere with the whole amount at once.[1] I have shown how the deposit in the atmospheric bank can be maintained through the receiving teller while the paying teller is constantly releasing it in response to checks on demand.

Meanwhile I have given you a glimpse down some of the long vistas of geologic time. I have brought before you

1. An interesting possibility—I may say, from some points of view, a probability—would lead us too far here, if we were to attempt its discussion. But there is nothing unlikely in the supposition that the whole oxygen of the atmosphere has been set free from its combination in the form of carbon-dioxide by the action of plant-life. Such a supposition is beset with some difficulties, not, perhaps, insuperable, but it has many strong reasons in its favor.

some of the processes of world making—some actual records of æons long gone by—some relics of remote conditions entombed when time was young. You have, in imagination, seen the glowing lithosphere slowly cooling and crystallising and as the solid earth was built there were stored in its foundation stones these samples of its primeval atmosphere, sealed in their crystal flasklets. The building advances, the cooling nucleus contracts, the cold and solid crust outside, being unsupported, sinks and is crushed. You hear, as it were, the creaking of the massive globe as its crystalline particles yield before the inconceivable earth-force. Then —in that time, not of disaster and catastrophe, but of slow, imperceptible evolution—were graven on stone those mystic characters which the microscope has interpreted to you this evening.

APPENDIX.

(*a*) Amount of coal in the earth :

This is based on an estimated area of the world's coal field equal to 500-000 square miles, with an average total thickness, including thick and thin beds, of twenty feet.

The result gives a layer of coal over the globe one-twentieth of a foot thick.

(*b*) Amount of carbon-dioxide and carbon in the atmosphere :

This equals by volume, $\frac{1}{3300}$; by weight, $\frac{1}{1666}$.

The other data are as follows :

Area of globe	200,000,000 sq. m.
Depth of air, if of uniform density	5.4 m.
Hypothetical density of carbon vapor	0.418
Specific gravity of coal	1.3
Specific gravity of water to air	817.

Result as given in text.